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(54) A METHOD OF MONITORING UNDERGROUND PROCESSES

(71) We, DEUTSCHE TEXACO AKTIENGESELLSCHAFT, a German company, of Überseering 40, 2000 Hamburg 60, Federal Republic of Germany, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

The present invention relates to a method of monitoring underground processes in which material property changes of underground formations occur within a limited area.

The method allows the determination of the extent of the changed area and the degree of change of the material properties.

The underground processes are especially concerned with insitu combustion and gasification processes in petroleum and coal deposits, oil shale, and tar sands. The leaching of salt caverns and mining operations which cannot be directly tracked within the process zone, can also be observed.

The principle of underground combustion is based on the change of physical properties which is effected by generating heat in the reservoir, e.g. phase conversion of raw material, so as to improve its flowability or to render flowability possible.

Examples of this kind include crude oil recovery by means of insitu combustion, or sulfur recovery by means of the Frash process. In these processes, partial combustion is initiated in one part of the reservoir and is maintained by means of an oxygen-containing gas.

The process of coal gasification is particularly suited for the recovery of coal at depths below approximately 1000 to 1200 metres, a depth which practically constitutes the limit in conventional mining. According to this method, a coal seam is penetrated by an injection well through which a feedgas is injected thereby effecting a chemical reaction, for example partial combustion, of the feed gas with the coal in the seam. The resultant process gas moves outward through fissures which possibly enlarge during the process itself, towards a number of production wells which, for instance, encircle said injection well. The reaction front divides the coal seam in two parts: In an inner, cylindrically shaped part, in which injection gas and process gas are present and an outer part substantially consisting of the unaffected coal which, however, is fissured. These fissures, also contain process gas which propagates towards the production wells.

Large scale tests as well as application on a technical scale render monitoring of the critical process parameters necessary during operation. These parameters include pressure and temperature in the inner area, in particular at the reaction front, and the position of the reaction front. It appears that the inaccessible location and the high temperatures in the reaction zone make direct measurement very difficult. Such process monitoring methods were not previously known. As secondary and tertiary process for oil recovery and coal gasification processes become more and more important with increasing shortage of raw material and energy, there is also a greater demand for observing the performance of these processes which take place in inaccessible underground strata.

The present level of technology allows information to be obtained on the parameters of the geological strata by way of geophysical measurements, which may be thermal measurements, electrical measurements, or seismic measurements, i.e. recording the noise which occurs during combustion, gas flow, or the enlarging of fissures. They may also concern active measurements where a seismic wave is preduced on the earth's surface and the reflections at the combustion front are observed.

Passive seismic measurements can theoretically be used in the determination of the

position of the noise source when the instant of receiving one and the same noise at several boreholes can be determined.

The difficulty lies in correlating the different noise signals occurring in different boreholes. Therefore information can only be related to the average intensity of noise development. Active seismic processes, for example, corresponding to the seismic reflection process as developed in petroleum exploration to highest perfection, fundamentally allow the determination of the position of a discontinuity in the material properties, and under favourable conditions, information can be given on the nature of changes of the material properties. The great distance between the combustion front and the surface and the fact that the lateral position of the front is the decisive parameter, do not permit the simple application of methods used in petroleum prospecting to the process monitoring in subterranean processes: The geometric conditions require that the seismic wave source and the positions of the observation for the seismic wave at the geological strata level be distributed to one or more boreholes. This requirement restricts the kind of excitation of seismic waves and also the amplitude of the exciter wave, since the integrity of borehole and deposite must be warranted during measurement. Another difficulty is that the area enclosed by the reaction front must be determined by the time the distance from the source of the front is only a few metres. As the geometric dimension of the changed area must be of the same order of magnitude as the average wave length of the emitted signal, this requires the use of wave lengths preferably of the order of magnitude of about 1 to 20 metres. A further difficutly is that the relatively small object will essentially diffract and scatter the seismic waves and reflect them to only a small extent. The receiver used must therefore be capable of recording very weak signals. By using the known seismic reflection method a method was found whereby each geological stratum in which changes are expected, precise, reproducible, time-seismic signals are emitted, which are recorded in the same geological stratum, on one or more different positions or, in the same position stacked with signals of reverse sign, and by which the magnitude of the so obtained differential signals and their propagation time are measured.

According to the invention there is provided a method of monitoring underground processes to localise and determine the degree of change of material properties of underground strata effected by the processes wherein exactly reproducible time-sequential seismic signals are emitted in each geological stratum where changes are expected to take place and recorded at one or more positions in the geological stratum characterised in that signals which are respectively emitted and recorded with a significant time difference in relation to the progress of the underground process are stacked with reverse signs, and the difference signals thus obtained are measured according to magnitude and propoagation time.

The invention will now be described by way of example with reference to the accompanying drawings wherein:-

Figure 1a is a horizontal section of a reservoir; and

Figure 1b shows a vertical section through the reservoir.

The reference symbols represent

1 = ignition and injection well

2 = well in which signals are generated

3 = production wells

4 = well in which signals are recorded

5 = section of changed material properties (reaction zone)

6,7 = signal paths

8 = signal source

9 = signal receiver

10 = geological stratum

Preferably, the signals are composed of a number of weak identical single signals which, subsequent to being received, are stacked synonymously and synchronously so as to provide a summation signal. Minimum discernible signals are to be emitted to prevent a change of the geological stratum 10, i.e. the induced mechanical voltage must remain below the load limit of the stratum. It is thus suggested - in contrast to conventional practice - to use an interference process whereby the seismic wave field is firstly observed before ignition in the reaction zone (5) and then after ignition. General changes in the wave area are determined by way of later measurements. In this instance, it is not decisive whether these changes are

determined in relation to the conditions before ignition or after, but one may expect that the changes in relation to condition before ignition to be more significant than after ignition, thus rendering their determination much easier.

Seismic interference measurements, i.e. the exact comparison, for instance, by subtracting (stacking with reverse sign) two seismic recordings with very slight changes of wave propagation conditions with the aim of determining these changes, were previously now known. Such an interference measurement requires that the waves to be compared are generated in exactly the same way as otherwise changes of the wave field can no longer be correctly related to the changes in the reaction zone (5). It is therefore imperative to maintain the highest possible signal stability at source.

The absence of interference is also necessary for a successful utilisation of active seismic methods. However, the noise which was mentioned in discussing the passive seismic methods, is always present and would thus simulate a change in the wave field. It is therefore necessary with this method that the signal-to-noise ratio be considerably improved. To meet the above mentioned requirements, it is suggested that a low-amplitude repetitive signal be used. Basically, these requirements can be met by any repetitive signal when one "stacks" a random number of signal observations, preferably in the order of from about 100 to 1000, since the noise due to its statistical nature, increases only with the square root of the number of stacks whereas the strength of the signal increases proportional to the number of stacks.

The preferred solution to the problem is effected by using a vibrator (8) which generates a so-called "sweep". A "sweep" is a signal in accordance with the equation

$$S(t) = a(t) \,.\, \sin(\varphi(t))$$

with the function of amplitude

$$a(t) = 0 \text{ for } t<t_1,\ t>t_2;\ a(t)>0 \text{ for } t_1 \leq t \leq t_2$$

with the function of phase

$$\varphi(t), \frac{d^2}{dt^2}\varphi \neq O$$

This corresponds to a time-limited sinusoidal wave train $a(t) \sin \omega t$, the term ωt, however, is replaced by the phase function $\varphi(t)$. "Instantaneous frequency" is the differential quotient $d\varphi/dt$. It follows from the condition $d^2\varphi/dt_2 \neq 0$ that the instantaneous frequency of a sweep is a highly monotonous function, i.e. a function either constantly increasing or constantly decreasing but never has the same value, not even for two directly successive points of time. With the preferred technical solution the instantaneous frequency varies between about 100 Hz and about 1200 Hz in a time interval of from about 1 to 10 seconds. Autocorrelation of the sweep results in the autocorrelation function $s(\tau) = \int_{-\infty}^{+\infty} S(t).\ S(t - \tau)dt$, which is symmetrical and has a marked maximum for $\tau = 0$. Interfering secondary maxima can be mimimized by selecting a suitable amplitude function $a(t)$ and phase function $\varphi(t)$. Since the energy in the sweep is proportional to the intergral

$$\int_{t_1}^{t_2} a^2\, dt < a^2_{max} \,.\, (t_2 - t_1)$$

and a_{max} is limited by the load capacities of well 2 and of the traversed rock, it is more favourable to perform the minimizing by selecting $\varphi(t)$ alone and by the selection of a constant for $a(t)$ $t_{11}<t<t_{22}$ with the closest possible value to a_{max}.

t_{11} and t_{22} are points of time in the interval t_1, t_2 such as $t_1 < t_{11} < t_{22} < t_2$

$$\frac{t_{11} - t_1}{t_2 - t_1},\ \frac{t_2 - t_{22}}{t_2 - t_1} \ll 1$$

The recorded signals are the stacked sweep signals which arrive at the receiver via different paths (and due to this, with time lag). By cross-correlating the recorded and stacked signals with the emitted sweep, each of the sweep signals corresponding to a distinct path (a certain time of arrival) is contracted in the known manner to the autocorrelation function of the sweep. In this way the signal obtained after cross-correlation could have been received if an impulse had been emitted in the form of an autocorrelation function.

This technique is known in other frequency ranges for instance, in reflexion seismics and radar technology. Its application for locating changes of the material properties during recording by way of interference measurement, is relatively new. The signals received are converted preferably in known manner into digital signals and are stored, stacked in an onsite computer and finally cross-correlated with the emitted signals which are also stored in digital form.

The propagation time from signal source (8) via the process zone to receiver (9) depends on the length of paths (6,7) and on the seismic velocity in this line. The significance of the changes to be expected in the wave field, depends - apart from the size and boundary of the changed area and the wave length of the emitted signal - on the magnitude of change of the material properties in the process area and on the gradient of change in the process area.

It is possible to draw one's conclusions from the gradient of change occurring in the wave field with respect to the product of density and propagation velocity of stress waves. Since this

product is dependent on the other process parameters, especially on pressure and temperature, there is a possibility of determining more than only the locality or change of process parameters.

It is possible to place two receivers at different depths within the geological stratum in order to record the amount of vertical changes when the said stratum is of greater thickness.

WHAT WE CLAIM IS:-

1. A method of monitoring underground processes to localise and determine the degree of change of amterial properties of underground strata effected by the processes wherein exactly reproducible time-sequential seismic signals are emitted in each geological stratum where changes are expected to take place and recorded at one or more positions in the geological stratum characterised in that signals which are respectively emitted and recorded with a significant time difference in relation to the progess of the underground process are stacked with reversed signs, and the difference signals thus obtained are measured according to magnitude and propagation time.

2. A method as claimed in Claim 1 wherein a signal is used for forming said difference, said signal being recorded before the beginning of an underground process.

3. A method as claimed in either Claim 1 or 2 wherein summation signals with reversed signs are stacked as signals with a significant time difference, the summation signals being obtained by synchronously and symmetrically stacking at least two individual signals with a non-significant time difference in relation to the progress of the underground process.

4. A method as claimed in Claim 3 wherein a borehole vibrator is used as the signal source which emits single signals being substantially sinusoidal with an instantaneous frequency varying highly monotonously between upper and lower frequencies within a predetermined period of time, and cross-correlating the received signals prior to stacking so as to provide a summation signal or cross-correlating the summation itself subsequent to stacking, with the emitted signal.

5. A method as claimed in any preceding claim wherein the signals to be emitted are present as a digital time series which are, prior to emittance, converted into analogue form, and said received signals are reconverted into digital form immediately after being received.

6. A method of monitoring underground processes substantially as hereinbefore described with reference to the accompanying drawings.

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1588693 COMPLETE SPECIFICATION

1 SHEET *This drawing is a reproduction of the Original on a reduced scale*

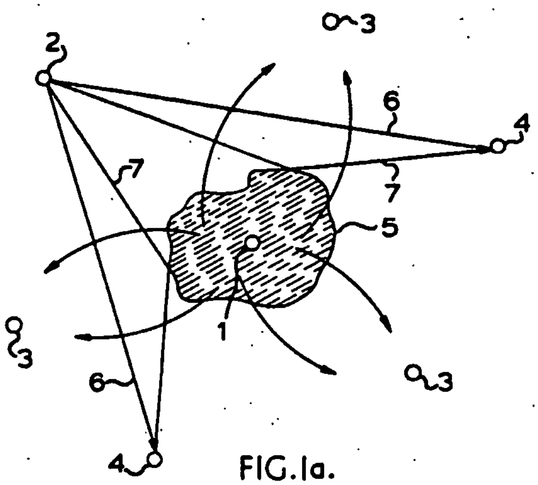

FIG.1a.